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3 authors, including:

Abdullah Al Shadi
Khulna University of Engineering and Technology

Bijoy Sorker
Khulna University of Engineering and Technology

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Abdullah Al Shadi
Electrical and Electronic Engineering
Khulna University of Engineering & Technology
Khulna, Bangladesh
abdullahalshadi7@gmail.com

Md. Nur Kutubul Alam
Electrical and Electronic Engineering
Khulna University of Engineering & Technology
Khulna, Bangladesh
nur.kutubul.alam@eee.kuet.ac.bd

Bijoy Sorker
Electrical and Electronic Engineering
Khulna University of Engineering & Technology
Khulna, Bangladesh
sorkerbijoy.eee.kuet@gmail.com

***Abstract*— Advanced semiconductors, such as gallium nitride (GaN) compounds, are revolutionizing the field of power electronics. GaN-based materials, specifically GaN HEMTs, exhibit exceptional efficiency in high-frequency and high-power usage due to their unique characteristics. However, despite their potential, GaN components face significant challenges such as deterioration and power loss caused by electrical charge trapping, which restricts their widespread application. Understanding the origins and influence of these traps on device performance remains a critical area of research. This study presents a simulation-based investigation of the effects of carbon-induced traps in AlGaN/GaN HEMTs. The simulation model, implemented using TCAD software, simplifies certain aspects of the device while incorporating essential parameters such as background doping, trap density, activation energy, and capture cross-section to realistically mimic the behavior of carbon traps. The results provide insights into the detrimental impacts of these traps on device performance and suggest strategies to mitigate their effects, contributing to the optimization of GaN HEMTs for high-power and high-frequency applications.**

***Keywords*— GaN HEMT, Carbon Trapping, TCAD, Device Performance, Threshold Voltage, Leakage Current**

I. INTRODUCTION

In the past few years, Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) have drawn significant attention owing to their remarkable features compared to conventional silicon-based devices. AlGaN/GaN HEMTs are frequently used in high-power [1], high-frequency [2], and high-temperature [3] applications owing to their elevated breakdown voltage [4], superior electron mobility [5], and wide band gap [6]. These attributes make them suitable for power amplifiers, microwave transceivers, and switching power supplies.

A major issue is ‘charge trapping’, which results from the complicated nature of GaN-based heterostructures [7]. The complexity originating from the material's polarized crystal structure may offer both bulk and surface traps that serve as electron confinement sites, influencing device performance through phenomena like current collapse and self-heating during operation [8]. Current collapse refers to the phenomenon where electrons become trapped, leading to a transient reduction in drain current [9]. This instability might affect both device reliability and signal integrity. One major obstacle limiting the widespread commercial use of GaN-based devices is the insufficient comprehension of the origins of traps in GaN and their effect on the device's current attributes.

Although in AlGaN/GaN HEMTs, there are several traps, including carbon, iron, nitrogen vacancies, oxygen impurities, hydrogen-related defects, dislocations, and surface/interface states, substantially influence device performance and reliability [10], [11]. 'Carbon acceptor traps' and 'nitrogen vacancies' are paramount, directly affecting current collapse, threshold voltage instability, and leakage currents, rendering them essential focal points in research for high-power and RF applications [12], [13].

Recent advancements in GaN HEMT research have provided further insights into the detrimental effects of carbon-induced traps, which are introduced during the epitaxial growth process [13]. These traps significantly impact device performance by causing threshold voltage shifts, ON-state current degradation, and reduced reliability over time [1]. Studies have also proposed mitigation strategies such as optimizing doping profiles and improving epitaxial growth techniques to address these issues [14]. These advancements underscore the importance of further investigating the characteristics and mitigation of carbon traps to enhance device stability and efficiency.

Carbon-induced traps significantly affect long-term reliability due to their widespread occurrence, difficult management, and deep-level trapping effects [15], [16]. These traps are challenging to manage and have been shown to impair device reliability and dynamic performance over time. The inadvertent incorporation of carbon during epitaxial growth amplifies these issues, necessitating enhanced growth control techniques and trap management strategies. Understanding the behavior and characteristics of carbon traps under different conditions is therefore essential for developing effective methods to mitigate their impact. By reducing the detrimental effects of carbon traps, the efficiency, reliability, and long-term stability of AlGaN/GaN HEMTs can be significantly improved.

This study investigates the characteristics and impact of carbon-induced traps in the GaN buffer layer. By simulating the influence of critical parameters such as trap density, activation energy, and capture cross-section, this work aims to provide insights into the mechanisms underlying carbon trapping. These findings can guide the development of practical strategies to optimize GaN HEMT performance and enhance the commercialization potential of these devices for high-power and RF applications.

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II. Device Architecture and Model

This simulation depicts a two-dimensional $Al_{0.25}Ga_{0.75}N/GaN$ HEMT configuration with a gate length of 300 nm, as illustrated in Fig. 1. The gate-source distance (L_{gs}) is 4.55 µm, and the gate-drain distance (L_{gd}) is 8.35 µm. An unintentionally doped AlGaN barrier layer, 15 nm thick, is deposited on a 1 µm GaN buffer layer. The mole percentage of aluminum in the barrier layer is 25%. The device architecture simplifies the simulation by excluding the GaN cap and AlN spacer layers, focusing instead on the core structure to investigate the effects of carbon traps. Ohmic contacts are defined at the source and drain terminals using heavily doped donor regions to facilitate current flow. Surface donor traps are included in the simulation, positioned at an energy level of E_d=0.45 eV below the conduction band, with a concentration of $1.5\times10^{13}cm^{-2}$.

The buffer layer is carbon-doped, functioning as a deep acceptor. The doping concentration is $2\times10^{17}cm^{-3}$. The energy level is positioned at 0.5 eV beneath the conduction band [17]. In this simulation, self-heating has been disabled to focus on the performance decrease caused by traps. The capture cross-section for the carbon traps is set to 10^{-15} cm^2 [18], which represents typical values observed in experimental studies of deep-level traps.

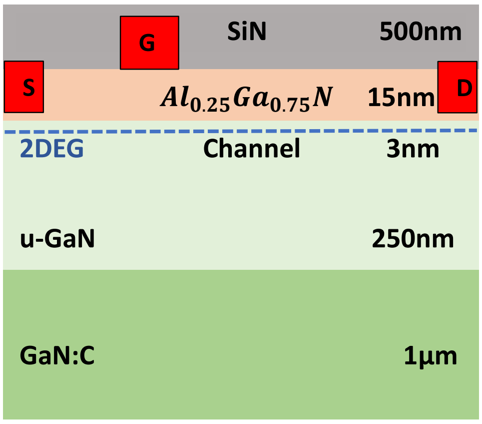


Fig.1. Schematic of the structure being used for the simulation.

TABLE I. The parameters for the simulation. [19]

Material	E_g [eV]	ϵ_r	μ_n [cm^2/Vs]	v_s [cm/s]	χ [eV]
$Al_{0.25}Ga_{0.75}N$	3.91	10.287	100	1.12e7	2.22
Channel GaN	3.42	10.28	2250	6.6e6	2.56
UID GaN	3.42	10.28	200	6.6e6	2.56
C:GaN	3.42	10.28	200	6.6e6	2.56
AlN	6.13	10.31	-	2.17e7	0.663
Si	1.12	11.7	1000	2.4e7	4.17

To isolate the effects of trapping on device performance, self-heating effects are disabled in this simulation. This simplification ensures the results focus solely on the degradation caused by charge trapping mechanisms. The selected parameters, including the energy levels, trap densities, and doping concentrations, are consistent with known values for carbon traps in GaN as reported in prior experimental and theoretical studies, ensuring the physical relevance of the simulation model.

III. Simulation Result And Discussion

Simulations were performed to examine the effect of acceptor-like traps in the buffer GaN on the device's static characteristics. The simulations were conducted on a basic AlGaN/GaN HEMT structure, simplifying the model by excluding the strain relief layers. The schematic utilized for this simulation is depicted in Fig.1. Voltages are directly applied to the metal contacts (drain, gate, and source). The gate contact/AlGaN barrier interface functions as an ideal Schottky contact, preventing current flow through the contact. Meanwhile, the drain and source/channel interface serve as ohmic contacts, facilitating current flow through them. The buffer GaN layers (channel, u-GaN, GaN: C) are inserted with an n-type background doping of $1x10^{15}cm^{-3}$. The carbon-doped buffer GaN is achieved by incorporating deep acceptors through the adjustment of various trapping parameters: the trap-level E_a positioned from the valence band, along with a density of N_{ta} and a hole capture cross-section of σ_p.

A. Analysis of the influence of varying trap parameters on Threshold Voltage

Transfer characteristics curve that specifies the drain current (I_d) versus gate voltage (V_{gs}) for a drain voltage (V_{ds}) from 0.2 V to 1 V in an increment step of 0.2 V has been illustrated in Fig.2 when the trap was absent.

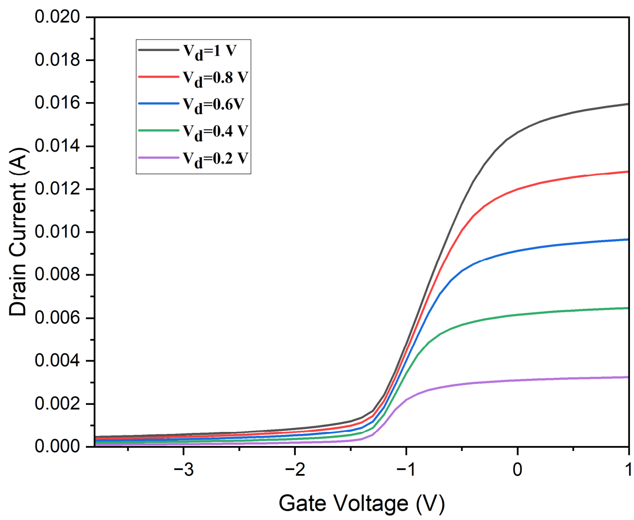
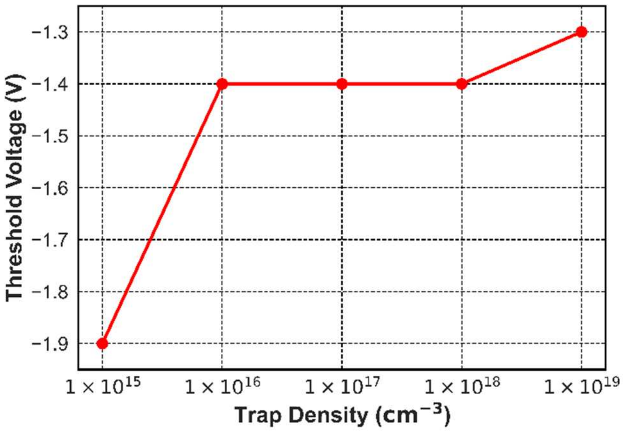


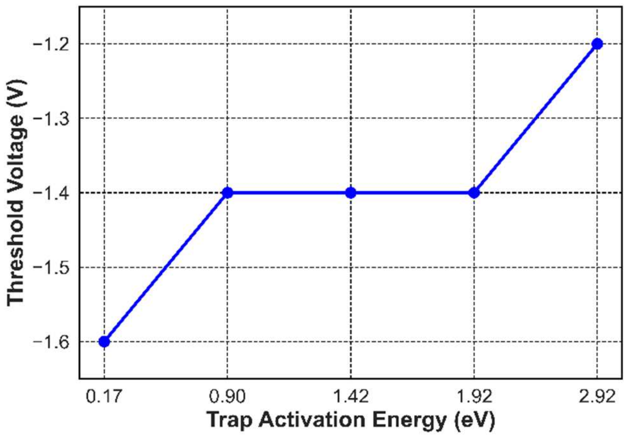
Fig.2. Simulated model of transfer characteristics of the device without trap.

Now, to analyze the impact of varying trap parameters on threshold voltage, a plot illustrating the change in threshold voltage versus N_{ta} /E_a /σ_p is presented in Figure 3.

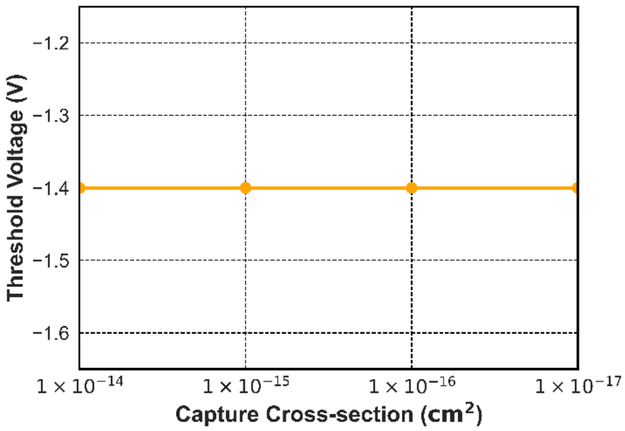
In Fig. 3(a), the threshold voltage of the AlGaN/GaN HEMT increases with the elevation of acceptor trap density. At a trap density of $1x10^{15}cm^{-3}$, the threshold voltage is -1.9V. As the trap density rises to $1x10^{16}cm^{-3}$ the threshold voltage escalates to –1.4V. However, the figure indicates that upon further raising the trap density to $1x10^{18}cm^{-3}$, there was no substantial change, and the threshold voltage remained at -1.4V. With the trap density further elevated to $1x10^{19}cm^{-3}$ the threshold voltage has subsequently risen to -1.3V. Also, it has been a device with a greater trap density that demonstrates a diminished drain current at an equivalent gate voltage.



(a)



(b)



(c)

Fig.3. Threshold voltage for different (a) acceptor trap density, (b) trap activation energy and (c) trap capture cross-section for a fixed background doping ($1x10^{15}cm^{-3}$).

Meanwhile, Fig. 3(b) demonstrates an increase in threshold voltage change as trap levels approach nearer to the valence bands. The threshold voltage for the trap activation energy of 0.17 eV is -1.6V. As the trap activation escalates to 0.90 eV, the threshold voltage has similarly risen to -1.4 V. However, for an additional rise to 1.42 eV and 1.92 eV, the threshold voltage remained unchanged at -1.4 V. Subsequently, with a further elevation of the activation energy to 2.92 eV, the threshold voltage increased once more, reaching -1.2 eV.

Fig. 3(c) demonstrates that there is no variation in threshold voltage across varied trap capture cross-sections. Indicates that the cross-section does not influence the threshold voltage, regardless of whether it increases or not. The threshold voltage will remain unchanged.

These findings highlight the need to prioritize controlling N_{ta} and E_a and during epitaxial growth to ensure stable threshold voltage performance.

B. Analysis of the influence of varying trap parameters on ON Current

The output characteristics curve demonstrating the drain current (I_d) to the drain voltage (V_{ds}) for a gate voltage (V_{gs}) ranging from 0 V to -4 V, is presented in Fig. 4. This figure indicates that the drain current is higher in the absence of traps.

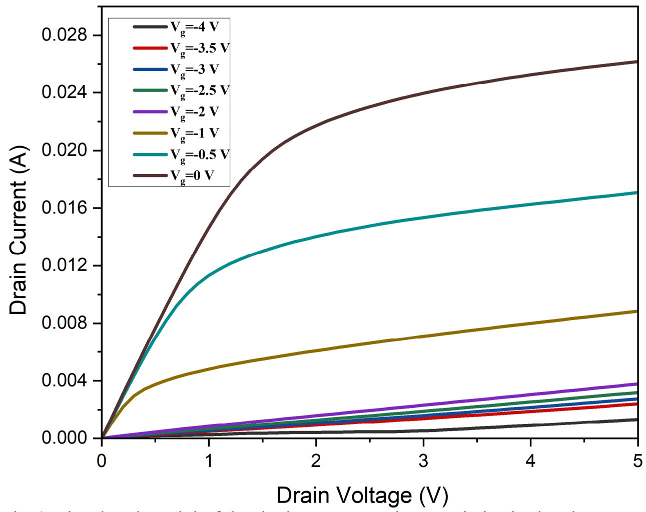
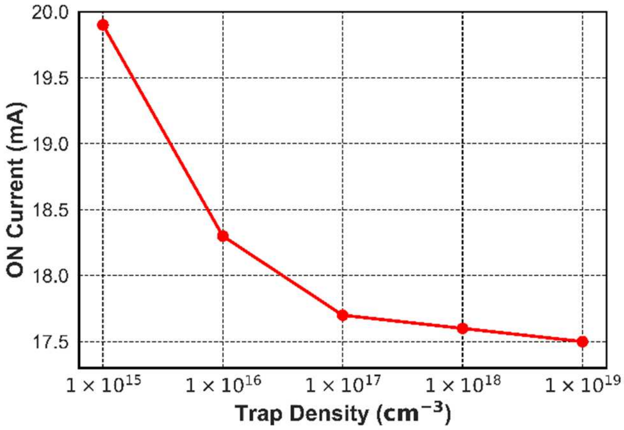


Fig.4. Simulated model of the device's output characteristics in the absence of traps.

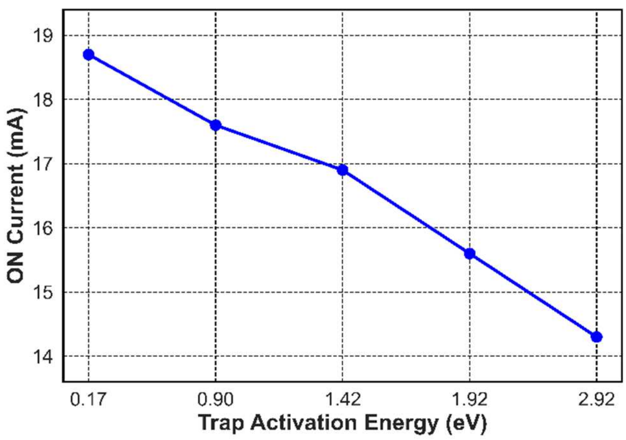
Now, to analyze the impact of varying trap parameters on 'ON state Current', a plot illustrating the change in ON state Current versus N_{ta} /E_a /σ_p is presented in Fig. 5. The value of V_d has been kept as 5V.

Fig. 5(a) clearly demonstrates that the ON current of the AlGaN/GaN HEMT diminishes with an increase in acceptor trap density. The device's ON current at $N_{ta} = 1x10^{15}cm^{-3}$ is 20 mA. The augmentation of trap density to $1x10^{16}cm^{-3}$ has resulted in a reduction of the ON current to 18.30 mA. With an additional increase in trap density to $1x10^{17}cm^{-3}$, the ON current decreased to 17.70 mA. With a further increase in trap density to $1x10^{18}cm^{-3}$, the ON current decreased to 17.60 mA. In the last scenario, when the trap density was elevated to $1x10^{19}cm^{-3}$, there was a slight decrease in the ON current, which measured roughly 17.50 mA. This figure illustrates that, although the initial increase in trap density resulted in a substantial decrease in the ON current, subsequent increases in trap density produced only a minimal effect.

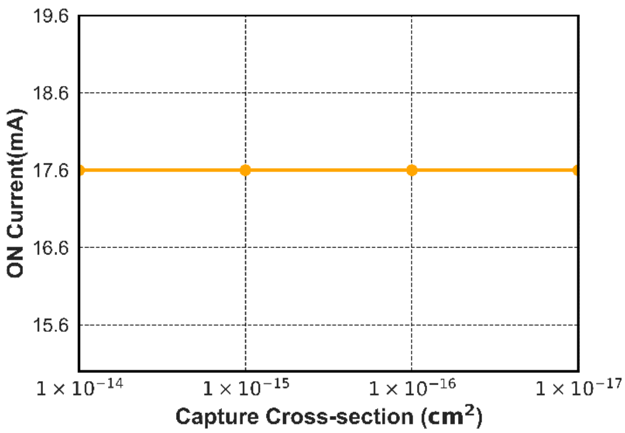
Fig. 5(b) illustrates that devices with elevated trap activation energy exhibit diminished ON current. At an activation energy of E_a = 0.17 eV, the ON current measures 19.90 mA. As the energy level increases to 0.90 eV, the ON current declines to 17.60 mA. A further increase to 1.42 eV results in a reduction of the ON current to 16.90 mA. When the energy level is raised to 1.92 eV, the ON current decreases to 15.60 mA. Finally, at an energy level of 2.92 eV, the ON current reaches approximately 14.40 mA. This data indicates that trap activation energy significantly influences the ON current, which decreases markedly with rising energy levels.



(a)



(b)



(c)

Fig.5. ON Current (extracted at V_d= 5V) for different (a) acceptor trap density, (b) trap activation energy, and (c) trap capture cross section for a fixed background doping ($1x10^{15}cm^{-3}$).

Fig. 5(c) demonstrates that there is no variation in ON state current across varied trap capture cross-sections. Indicates that the cross-section does not influence the ON current, regardless of whether it increases or not. The ON current will remain unchanged.

This indicates that reducing trap density and optimizing activation energy are more effective strategies for enhancing ON-state current performance.

C. Summary and implications

The results indicate that carbon-induced traps significantly affect the electrical performance of AlGaN/GaN HEMTs. Trap density and activation energy are critical parameters that influence threshold voltage shifts and ON-state current degradation.

The findings of this study align well with reported trends in the literature, validating the simulation model's credibility. These insights can guide strategies to mitigate the adverse effects of carbon traps, such as optimizing doping profiles, employing compensating dopants, and improving material growth techniques. This work provides a foundation for enhancing the reliability and performance of GaN-based devices for high-power and high-frequency applications. Furthermore, these mitigation strategies are pivotal for advancing the commercialization of GaN HEMTs in industries requiring consistent and efficient device performance.

D. Experimental Validation and Future Work

While this study is based on simulation results, experimental validation is critical to support the findings. Techniques such as Deep Level Transient Spectroscopy (DLTS) can be employed to measure trap characteristics, including energy levels and densities. Transmission Electron Microscopy (TEM) can provide visual confirmation of trap distributions and their structural impact on the GaN buffer. These methods, when applied to actual GaN HEMT devices, would complement the simulation results and further elucidate the role of carbon-induced traps. Additionally, future studies could explore the temperature dependency of traps to provide a comprehensive understanding of device behavior under real-world conditions.

IV. Conclusion

Due to their elevated breakdown voltage, high electron mobility, and dense charge concentration, AlGaN/GaN HEMTs are pivotal in high-power, high-speed, and DC switching applications. However, performance degradation caused by charge trapping, particularly from carbon-induced traps in the GaN buffer, limits their effectiveness. This study presents a simulation model that incorporates the physical effects of carbon acceptor traps, which serve as deep-level trapping centres in the 2DEG channel. The results show that the presence of carbon traps significantly impacts the device's dynamic behaviour, leading to a reduction in conductance and current collapse. These findings align with prior research on the detrimental effects of carbon doping in GaN HEMTs and underscore the need for effective trap management in device design. The insights from this simulation provide a foundation for improving AlGaN/GaN HEMT performance by mitigating carbon traps. Optimizing doping profiles and refining epitaxial growth techniques can significantly reduce trap density, enhancing device reliability and efficiency. These strategies are critical for improving the stability of GaN-based devices under high-power conditions and advancing their commercialization for high-performance applications.

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